Upper flow regime bedforms on levees and continental slopes: Turbidity current flow dynamics in response to fine-grained sediment waves

Svetlana Kostic*
Computational Science Research Center, 5500 Campanile Drive, San Diego State University, San Diego, California 92182, USA

ABSTRACT
Our knowledge of submarine upper flow regime bedforms is very limited. Numerical experiments presented herein were designed to broaden our understanding of the origin and dynamics of fine-grained upper flow regime bedforms in turbidite systems, particularly on levees and continental slopes. The experiments combine field information in order to (1) examine the hydrodynamic response of a bed consisting of fine-grained sediment waves to a wide range of turbidity current conditions, and (2) demonstrate that fine-grained sediment waves most likely form and evolve as upper flow regime bedforms, i.e., cyclic steps, transitional bedforms, or antidunes. The results of the study provide valuable information for the reconstruction of turbidity current flow dynamics on levees, continental slopes, and in other submarine settings that display a slope break.

INTRODUCTION
Sediment waves on the seafloor and in the subsurface are increasingly recognized as common sedimentologic features of continental margins. However, their morphodynamics and formative flow dynamics in particular are not well understood. The upper flow regime bedforms are potentially very important in submarine environments, as their presence implies active processes and the transfer of terrigenous sediments across continental slopes by way of supercritical flows.

Fine-grained sediment waves, the focus here, are widespread in turbidite systems (Normark et al., 2002). They have been generally reported in areas where turbidity current flow is unconfined, such as the flanks of submarine channel levees (Normark et al., 1980, 2002; Flood et al., 1995; Migeon et al., 2000; Nakajima and Satoh, 2001; Fildani et al., 2006), some locations on the continental slope and rise (Jacobi et al., 1975; Damuth, 1979; Wynn et al., 2000a; Ercilla et al., 2002a), and the slopes of volcanic islands (Wynn et al., 2000b). Fine-grained sediment waves can also form in a confined canyon-channel environment; recent observations and morphodynamic modeling suggest that fine-grained sediment waves may play an important role in channel maintenance (Covault et al., 2014). Most fine-grained sediment waves display wave heights up to 80 m and wavelengths of as much as 7 km (Wynn and Stow, 2002). They form on relatively steep slopes (e.g., 0.7%–3% on levee flanks; Normark et al., 1980; Savoye et al., 1993), although some occur on nearly flat surfaces (Carter et al., 1990, Nakajima and Satoh, 2001). The fields of fine-grained sediment waves can cover significant areas on the seafloor (up to several thousand square kilometers; Damuth, 1979). They typically consist of turbidite silts and muds, interbedded with pelagic/hemipelagic sediments. Thin sands (a few centimeters) are frequently observed (Normark et al., 2002). Individual turbidite beds are generally coarser and several times thicker on the stoss side than on the lee side of waves (Flood et al., 1995; Nakajima and Satoh, 2001; Normark et al., 2002). This differential accretion results in the overall pattern of upslope and upcurrent migration of fine-grained sediment waves (Lee et al., 2002). In contrast, alternating hemipelagic caps generally have nearly uniform thickness, which indicates uniform settling of hemipelagic suspension and little or no erosion by successive turbidity currents. The cross-sectional geometry of fine-grained sediment waves varies from nearly symmetrical to slightly upslope asymmetrical, suggesting a more active vertical aggradation than an upslope migration (Migeon et al., 2000; Normark et al., 2002; Kostic, 2011).

WAVE FORMATION AND EVOLUTION
Normark et al. (1980) interpreted fine-grained sediment waves as antidunes that form beneath standing waves at the upper interface of a turbidity current; their antidune model below is referred to as the Normark’s model. Many have adopted the Normark’s model (Kubo and Nakajima, 2002; Lee et al., 2002), mainly because of the upslope migration of fine-grained sediment waves, their symmetrical cross-sectional geometry, and resemblance to antidunes reported from laboratory channels.

Some studies suggested that the waves might have been formed by internal lee waves (Lewis and Pantin, 2002) that are unlikely to be maintained by unsteady turbulent flows in which the pressure and density gradient are rapidly changing (e.g., Piper and Savoye, 1993; Nakajima and Satoh, 2001).

The physical constraint of the Normark’s model can be tied to supercritical flow regime via the densimetric Froude number Fr = 1. This dimensionless parameter is defined here as $Fr = U / \sqrt{ghH}$, where $U$ and $H$ denote the turbidity current velocity and depth respectively, $g$ is the acceleration of gravity, and $\phi$ is the fractional excess density due to suspended sediment and temperature gradient in turbidity currents.

The processes of initiation and evolution of fine-grained sediment waves are still debated. Lee et al. (2002) and Kubo and Nakajima (2002) used numerical and laboratory modeling to show that initial seafloor roughness (i.e., step-like perturbations) is normally required to initiate fine-grained sediment waves. Wynn and Stow (2002) discussed the importance of intervening hemipelagic sediments in the sediment wave growth. The numerical results of Lee at al. (2002) with step-like turbidite beds interbedded with hemipelagic/pelagic units revealed that hemipelagic deposition between individual turbidity currents enhances the upslope migration of fine-grained sediment waves. Kubo and Nakajima (2002) numerically generated several sediment waves from a flat bed, but had to use thousands of individual turbidite beds in a sequence.

Some studies advocate the concept of self-perpetuation as the primary mechanism of evolution of fine-grained sediment waves (Ercilla...
Upper flow regime bedforms on levees and continental slopes

Submarine antidunes, cyclic steps, and transitional bedforms between antidunes and cyclic steps (e.g., breaking antidunes, combination of breaking antidunes and cyclic steps, climbing antidunes on cyclic steps) are the upper flow regime bedforms. They result from the fundamental morphodynamic instability of Froude supercritical ($F_{Fr} > 1$) or near-critical ($F_{Fr} \approx 1$) flow over an erodible bed. Our knowledge on the origin and dynamics of submarine upper flow regime bedforms is still limited, and often relies on a direct analogy with fluvial upper flow regime bedforms. This analogy implies that a characteristic sequence of submarine upper flow regime bedforms (i.e., antidunes, transitional bedforms, and cyclic steps) gradually emerges as the flow energy increases (Cartigny et al., 2014). The flow energy herein is tied to the depth-averaged flow velocity $U$ via the densimetric Froude number $F_{Fr}$. The comparison between antidunes and cyclic steps was based on their geometry, internal structure and sedimentary facies, and/or migration pattern was presented in detail elsewhere (Fildani et al., 2006; Spinewine et al., 2009; Kostic, 2011; Cartigny et al., 2011); therefore, only a brief comparison relevant for analysis is provided below. Antidunes are short-wave symmetrical features that usually migrate upstream (for examples of less frequent downstream-migrating asymmetrical antidunes, see Engelund, 1970; Carling and Shvidchenko, 2002; Spinewine et al., 2009). Upstream-migrating antidunes may march in echelon (Normark et al., 2002), but are more likely to form, grow, and break cyclically in time due to their unstable and breaking nature (Alexander et al., 2001). Antidunes form by supercritical underflows (Normark et al., 1980) for which the turbidity current interface is in phase with bed. Cyclic steps, however, are long-wave phenomena in which the presence of internal hydraulic jumps in an overriding underflow stabilizes and preserves the morphodynamics of the flow-bed interaction (Kostic, 2011), which takes form of an orderly, upslope-migrating sequence of steps.

The term hydrodynamic response is used herein to signify (1) in-phase surface waves at the upper interface of a turbidity current in case of antidunes ($F_{Fr}$ exceeds the value of unity and displays in-phase oscillations); (2) a train of internal hydraulic jumps in case of cyclic steps ($F_{Fr}$ drops relatively sharply from a value exceeding unity before each jump to a value less than unity after each jump); and (3) a combination of in-phase standing waves and hydraulic jumps in the case of transitional bedforms (followed by a corresponding pattern of $F_{Fr}$).

FIELD-SCALE NUMERICAL EXPERIMENTS

We discuss fine-grained sediment waves formed and maintained by dilute turbidity currents in two very different submarine settings, i.e., on the inner levees of the Toyama Channel (in the Yamato Basin in the central Japan Sea (Fig. 1A) and on the inner margin of the Orinoco turbidite system, offshore South America (Fig. 1B). The Toyama Channel provides an illustrative example of a typical leveed submarine channel flanked with fine-grained turbidity current sediment waves. No evidence of contour currents has been found in this area. Roughly symmetrical, upslope-migrating Toyama sediment waves have wavelengths of 0.2–3.6 km and wave heights of 2–44 m. Nakajima and Satoh (2001) interpreted these sediment waves as non-antidune features formed by low-density turbidity currents overflowing channel banks, and hypothesized that the waves could have been instigated by large preexisting sand dunes. Spinewine et al. (2009) and Cartigny et al. (2011) suggested that Toyama sediment waves can be cyclic steps. Fine-grained sediment waves on the southern margin of the Orinoco valley, a segment of the Orinoco turbidite system (Fig. 1B), are interpreted as being formed beneath unconfined turbidity currents sourced from slope failures on the adjacent Venezuela, Guyana, and Suriname continental margins (Ercilla et al., 2002a). Sediment wave dimensions are highly variable across the wave field: wavelengths are 0.11–2.6 km, and wave heights 1–15 m (Fig. 1B). Their shape is mostly irregular due to underlying mass-flow deposits and mud diapirs, and they migrate upslope. A simple analysis of Ercilla et al. (2002a) based on $F_{Fr}$ (Normark et al., 2008) suggests that they have possibly formed as antidunes during part or all of their existence, in a manner similar to that reported for other turbidity current sediment wave fields (e.g., Normark et al., 1980; Wynn et al., 2000a).

The field-scale numerical experiments of Figures 2 and 3 were designed to (1) investigate the hydrodynamic response of a broad range of overriding turbidity currents to fine-grained sediment waves observed in different deep-sea settings (i.e., levees of the Toyama Channel and the continental slopes of Guyana and Suriname); and (2) use the information on turbidity current flow dynamics to loosely classify fine-grained sediment waves. The simulations were performed over a fixed present-day bed for the Toyama sediment waves (line 202, inner bank; Figs. 1A and 2) and over a present-day bed and paleoslope bed for the Orinoco sediment waves (TOPAS [topographic parametric sounder] line; PROFILES 1 and 2; Figs. 1B, 3A, and 3B).

In the first experiment (Fig. 2), the inflow Froude number $F_{Fr,i}$ was varied by assigning values of the inflow turbidity current depth ($H_l = 10$ m and $H_l = 250$ m), while keeping the inflow velocity $U_i$ and suspended sediment concen-
The higher value of $H_o$ was selected to be comparable to the levee relief of 280 m on the right side of the channel (Fig. 1A). Figure 2 illustrates that a wide range of overflows interacts with the Toyama sediment waves and suggests that the undulations are cyclic steps; for example, eight hydraulic jumps (where $Fr_d$ drops relatively sharply from a value exceeding unity to a value less than unity) can be identified for the lower flow depth ($H_o = 10$ m). As the upstream depth increases, however, the feedback of sediment waves on the flow dynamics weakens, with only two such jumps present for the deeper flow ($H_o = 250$ m). Figure 2 reveals other notable features, for example, (1) the bed and interfacial undulations for $H_o = 250$ m are in phase in the supercritical part of the flow, as expected for antidunes (Kennedy, 1963). This pattern indicates climbing antidunes superimposed on two bigger cyclic steps. This is in accordance with the observations from flume experiments, which showed that antidunes can be found together with (Spinewine et al., 2009) or superimposed on cyclic steps (Cartigny et al., 2009). (2) The underflow can start off as supercritical ($Fr_o = 3.33$ for $H_o = 10$ m), critical or subcritical ($Fr_o = 0.67$ for $H_o = 250$ m), and still trigger the hydrodynamic response typical of upper flow regime bedforms. That is because the underflow is no longer influenced by upstream conditions as it runs downslope and either accelerates or decelerates to accommodate $Fr_d$ values that are consistent with bed perturbations. Near-critical ($Fr_d = 1$) or supercritical ($Fr_d > 1$) overflows onto levees seem very realistic for a wide range of flow conditions in the main channel; only relatively thick overflows are likely to be subcritical. However, it is reasonable to assume that unconfined underflows on continental slopes can commence as either supercritical (relatively thin) or subcritical (relatively thick).

Composite Figures 3A and 3B illustrate the response of a wide range of unconfined turbidity currents (inflow depths from 50 to 500 m) to the
present-day and paleo-profiles of the Orinoco sediment waves, respectively. The modeling input parameters summarized below are very loosely based on Ercilla et al. (2002a), that is:

for the lower depth limit $H_o = 50$ m, $U_o = 0.8$ m/s, $C_o = 0.5 \cdot 10^3$ ($Fr_{do} = 1.26$); for the upper depth limit $H_o = 500$ m, $U_o = 0.5$ m/s, $C_o = 0.5 \cdot 10^4$ ($Fr_{do} = 0.79$). The results of numerical experiments suggest that unconfirmed turbidity currents can interact with the Orinoco present-day bed as a variety of upper flow regime bedforms (cyclic steps, transitional bedforms, or antidunes) depending on whether the flow conditions put bedforms in a long or a short wave regime (Fig. 3A). For example, the hydrodynamic response consistent with cyclic steps for $H_o = 50$ m changes to the one consistent with antidunes for $H_o = 500$ m. However, Figure 3B shows that, for the same range of flow conditions, the hydrodynamic response to the Orinoco paleobed shifts from cyclic steps (for $H_o = 50$ m) to transitional bedforms, that is antidunes superimposed on a single relatively weak cyclic step (for $H_o = 500$ m).

**NUMERICAL EXPERIMENTS OVER DESIGNED BED CONFIGURATIONS WITH SYMMETRICAL UNDULATIONS**

Hydrodynamic response of a wide range of flow conditions to a sloping seabed consisting of symmetrical undulations is given by the following function:

$$\eta = amp \cdot \sin (k \cdot x + \phi) - x \cdot S + \alpha,$$

where $\eta$ is the bed elevation (m), $x$ is the streamwise coordinate (km), $amp$ is the wave amplitude, i.e., half the wave height $h$ (m), $k$ is the wave phase (dimensionless), $\phi$ is the phase shift on the x-axis (km), $S$ is the bed slope when averaged over undulations ($\%$), and $\alpha$ is a dimensional constant (m) defined as

$$\alpha = \eta_o - amp \cdot \sin \phi.$$  

Here, $\eta_o$ is the elevation of the most upstream point ($x = 0$) on the bed.

The wavelength $\lambda$ and wave phase $k$ are related such that:

$$\lambda = 2\pi/k.$$  

Three different bed configurations were analyzed: CASE 1, long-wavelength bed ($\lambda = 3141.6$ m; $k = 2$); CASE 2, intermediate-wavelength bed ($\lambda = 1256.6$ m; $k = 5$); and CASE 3,
short-wavelength bed ($\lambda = 785.4$ m; $k = 8$). The remaining parameters in Equations 1–3 were kept constant for all three configurations: $\eta_o = 340$ m, $\phi = \pi/2$, $S = 8\%$, and $L/h = 100$. The length, $L$, of the undulated bed was comparable to field cases, i.e., $L = 26$ km.

The flow parameters were selected to allow for a broad range of flow conditions to be tested. The incoming flow energy was varied considerably ($Fr_{do} = 3.52–0.79$ for CASES 1 and 2; $Fr_{do} = 1.33–0.79$ for CASE 3) by assigning values of the inflow depth ($H_o = 50–1000$ m for CASES 1 and 2; $H_o = 350–1000$ m for CASE 3). The inflow velocity and suspended sediment concentration were kept constant ($U_o = 10$ m/s, $C_o = 0.01$). Figures 4A–4C summarize principal results of the experiments. Turbidity currents interact with the long-wavelength bed (CASE 1) as cyclic steps over the entire span of flow conditions (Fig. 4, A1-B1). As the flow energy increases, hydraulic jumps form further from the inflow point and get stronger. Only extremely thick turbidity currents ($Fr_{do} = 0.79$, $H_o = 1000$ m in Fig. 4, A1-B1) are likely to respond to the bed undulations as transitional bedforms. In contrast, turbidity currents spreading over the intermediate-wavelength bed (CASE 2) display a flow response that is, for most conditions, consistent with transitional bedforms (antidunes and cyclic steps within the same train), as illustrated in Figure 4 (A2-B2). Very thick turbidity currents can enforce the transition to a flow response consistent with antidunes, i.e., the flow interface in phase with bed undulations ($Fr_{do} = 0.79$, $H_o = 1000$ m in Fig. 4, A2), while thin underflows can potentially interact with the bed as cyclic steps ($H_o < 50$ m in Fig. 4, A2-B2). Cyclic steps in transitional mode display one more intriguing and important feature, labeled here as enlargement of cyclic steps, to describe two or more shorter steps merging together to form fewer longer cyclic steps (Fig. 4, A2-B2). The process appears to emanate from the downstream end of the flow field and travels upslope and upcurrent, likely due to the propagation direction of gravity waves in turbidity currents that form cyclic steps. Laboratory experiments have also shown that antidunes and cyclic steps of the same magnitude are unlikely to coexist in a single train of sediment waves, because an undulating bed that forms beneath breaking antidunes tends to amplify and create cyclic steps an order of magnitude larger (Carigny et al., 2014). Turbidity currents interacting with the short-wavelength bed (CASE 3) display a flow response consistent with antidunes for all flow conditions (Fig. 4, A3-B3). Numerical simulations indicate that flows propagating over this particular configuration cannot provide a physically meaningful response for flow energy exceeding $Fr_{do} = 1.33$.

Furthermore, a sensitivity analysis of the hydrodynamic response to bed configurations (CASE 1 and CASE 2) was carried out. The objective was to examine how the lower and upper limits of cyclic steps change if the inflow velocity and concentration of suspended sediment vary over a broad range of plausible inflow conditions. The results are summarized in Figure 5. The depth limits for the sensitivity analysis were selected as follows. The lower depth limit ($H_o = 50$ m, $Fr_{do} = 3.52$) loosely corresponds to the upper limit of inflow energy analyzed herein (i.e., $Fr_{do} \leq 4$), i.e., the upper limit of cyclic steps or, for the sake of brevity, the upper limit. The upper depth limit ($H_o = 500$ m, $Fr_{do} = 1.11$)
roughly indicates the transition from cyclic steps to transitional bedforms for CASE 2, i.e., the lower limit of cyclic steps, or, in short, the lower limit. Even though this transition occurs for significantly deeper inflows \( (H_0 = 1000 \text{ m}, \text{Fr}_{do} = 0.79) \) for CASE 1, the lower limit of cyclic steps of CASE 2 was used in the sensitivity analysis for both bed configurations to allow easy comparison. For evaluation purposes, the upper and lower limits established in Figure 4, A1-B2, were also shown as a solid red line in Figure 5, A1-B2, and a solid lime green line in Figure 5, C1-D2, respectively. The modeling input parameters were as follows: the inflow depth and concentration were kept constant (upper limit in Fig. 5, A1-B2, is \( H_0 = 50 \text{ m}, C_o = 0.01; \) lower limit in Fig. 5, C1-D2, is \( H_0 = 500 \text{ m}, C_o = 0.01)\), while the inflow velocity was widely varied (upper limit, \( U_o = 3.0–15 \text{ m/s}, \text{Fr}_{do} = 1.05–5.27; \) lower limit, \( U_o = 9.0–15 \text{ m/s}, \text{Fr}_{do} = 1.00–1.67)\). As illustrated in Figure 5, A1-B2, significant changes in inflow velocity do not alter the nature of hydrodynamic response (cyclic steps) to bed configurations in CASES 1 and 2. In general, high-energy supercritical flows are less likely to form cyclic steps, since they may not be able to decelerate sufficiently to generate internal hydraulic jumps (see Equation 1 in Kostic, 2011). Thus, if the inflow velocity increases (e.g., from \( U_o = 10 \text{ m/s} \) to 15 m/s), the flow has to dissipate additional energy (sequent depths increase) and hydraulic jumps become weaker (e.g., Chow, 1988). The flow momentum pushes cyclic steps farther downstream. Higher energy inflows interacting with undulations of intermediate wavelength (CASE 2, Fig. 5, A2-B2) seem to promote the process of cyclic step enlargement, pushing the hydrodynamic response into transitional bedforms sooner. However, if the inflow velocity decreases (e.g., from \( U_o = 10 \text{ m/s} \) to 3 m/s), the flow is even more likely to display a hydrodynamic response consistent with cyclic steps (Fig. 5, A1-B2). The findings for the upper limit of cyclic steps (Fig. 5, C1-D2) are consistent with previously discussed results. Higher energy flows are able to change the hydrodynamic response from cyclic steps to transitional bedforms. In the case of Figure 5, C1-D2 (\( U_o = 15 \text{ m/s}, \text{Fr}_{do} = 1.67)\), the transition is realized by a single cyclic step that is adorned with climbing antidunes upstream of the jump and some kind of subcritical bedforms downstream of the jump. Lower energy flows (e.g., \( U_o = 9 \text{ m/s}, \text{Fr}_{do} = 1.0)\) promote interaction with the bed as cyclic steps. The sensitivity of the hydrodynamic response to changes in concentration of suspended sediment was investigated by varying the inflow concentration significantly (upper limit is \( C_o = 0.005–0.01, \text{Fr}_{do} = 4.97–1.11; \) lower limit is \( C_o = 0.005–0.01, \text{Fr}_{do} = 1.57–1.11)\), while the inflow depth and velocity remained constant (upper limit is \( H_0 = 50 \text{ m}, U_o = 10 \text{ m/s}; \) lower limit is \( H_0 = 500 \text{ m}, U_o = 10 \text{ m/s})\). The results were not presented in a separate figure, since the lower bound of inflow concentration was found to produce a hydrodynamic response similar to that of the upper bound of inflow velocity, and vice versa (Fig. 5, A1-D2).

DISCUSSION

Phase diagrams or bedform discriminators have been widely used to quantify the formative regimes and characteristics of fluvial bedforms (Vanoni, 1974; Ashley, 1990; Van den Berg and Van Gelder, 1993; Parker, 2004). There is as yet no complete phase diagram for submarine bedforms. (But see Kostic, 2011; Cartigny et al., 2011, 2014). This study identifies formative flow conditions for fine-grained sediment waves on levees and continental slope in order to provide a basis for the first complete phase diagram of submarine upper flow regime bedforms. The results unambiguously demonstrate that a wide range of turbidity current flow conditions promotes the formation of submarine upper flow regime bedforms, in particular cyclic steps, in turbidite systems with slope breaks. For example, fine-grained sediment waves on levees are prevalently cyclic steps. In contrast, the hydrodynamic response of turbidity currents to fine-grained sediment waves on continental slopes can range from antidunes to cyclic steps. Transitional bedforms generated numerically in this study include antidunes and enlarging cyclic steps within the same train (e.g., Fig. 4, A2-B2), and climbing antidunes superimposed on cyclic steps (e.g., Fig. 5, C1-D2). Flume experiments (Spinewine et al., 2009; Cartigny et al., 2014) have shown a gradual transition between antidunes and cyclic steps, and an order of magni-
Cartigny et al. (2014) observed that if a large train of fluvial antidunes form and flow energy is still increasing, some antidunes start to break while others return to upper stage plane bed. This triggers a slightly undulating bed, which then amplifies and forms a larger cyclic step beneath the antidune train. These fluvial cyclic steps are an order of magnitude longer than antidunes. The results of this study also suggest that it is unlikely for submarine antidunes and cyclic steps of the same magnitude to form in a single train of sediment waves. The enlargement of cyclic steps by merging several undulations into one bigger cyclic step as the flow energy diminishes (Fig. 4, A2-B2) possibly explains how this length difference comes into being and how sediment waves evolve through time. Field observations corroborate this finding; sediment waves have been observed to sometimes merge together upsection so that younger sections of a wave field have fewer yet larger individual waves than older sections (Carter et al., 1990; Ercilla et al., 2002b).

Numerical experiments performed over the Orinoco sediment waves (Figs. 3A, 3B) establish cyclic steps as a plausible mechanism by which net-depositional fine-grained sediment waves can form and grow on the continental slope. These cyclic steps can be triggered by some form of preexisting perturbations (e.g., paleo-bedforms or salt diapirs: Nakajima and Satoh, 2001; step-like undulations: Lee et al., 2002; Kubo and Nakajima, 2002) or possibly self-initiate from a plane erodible bed under specific conditions that were not investigated here (but see Kostic and Parker, 2006, and Fiddani et al., 2006, for examples of self-initiation in net-depositional coarse-grained and net-erosional fine-grained sediment waves). As the bed consisting of cyclic steps builds up in time and the bed slope increases, the streamwise pull of gravity increasingly suppresses the ability of the flow to undergo internal hydraulic jumps and form cyclic steps (Kostic, 2011). Therefore, transitional bedforms or antidunes are expected to take the place of cyclic steps on relatively steep slopes for most flow conditions.

It is also possible that sediment waves on continental slopes initially form as antidunes, which then break, amplify, and merge into larger cyclic steps in a manner similar to fluvial antidunes in experiments of Cartigny et al. (2014). However, this sequence of bedforms would imply that the flow energy increases as the system evolves in time, which seems unlikely.

The conditions under which net-depositional fine-grained near-cyclic steps with symmetrical cross-sectional geometry can self-initiate from a

Figure 4 (continued).
plane erodible bed deserve further investigation; these conditions have not been identified in previous studies (e.g., Kostic and Parker, 2006; Filardi et al., 2006; Kostic, 2011; Cartigny et al., 2011). The importance of pre-existing perturbations in the initiation of fine-grained cyclic steps warrants further evaluation as well.

CONCLUSIONS

1. The assumption of the Normark’s model that fine-grained sediment waves form as antidunes is valid in some submarine environments.
2. In turbidite systems that display a slope break, fine-grained sediment waves with long wavelengths are most likely cyclic steps, while sediment waves with short wavelengths most likely form or grow as antidunes. Fine-grained sediment waves of intermediate wavelengths are likely to be transitional bedforms (i.e., trains of antidunes and cyclic steps, or climbing antidunes superimposed on cyclic steps).
3. Fine-grained sediment waves on levees are unambiguously identified as cyclic steps over a broad range of flow conditions, since upper flow regime transitional bedforms can be generated only by unrealistically thick overflows, with depths comparable to the main channel relief.
4. Fine-grained sediment waves on continental slopes can form as any of the upper flow regime bedforms. The likelihood of relatively thick turbidity currents and high-gradient beds on continental slopes sways the interpretation toward transitional bedforms and possibly antidunes.
5. Since turbidity currents are rapidly no longer influenced by upstream conditions, no specific inflow regime (supercritical, critical, or subcritical) seems to be required for fine-grained sediment waves to grow and migrate once the initial wavy topography is established.
6. The results presented herein can be extended from levees and continental slopes to other submarine settings that display a slope break.
ACKNOWLEDGMENTS

This manuscript is dedicated to the memories of Dr. Vladislav Kostic, my beloved father, and Dr. William R. Normark, a friend and a mentor.

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Figure 5 (continued).
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